Compendium of Total Ionizing Dose (TID) Test Results for the Europa Clipper Mission

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Abstract—**This paper reports recent total ionizing dose (TID) test results post 300 kRad(Si) for a variety of common part types evaluated for use on NASA/JPL's Europa Clipper mission.**

I. INTRODUCTION

NASA's Europa Clipper (EC) mission aims to send a radiation tolerant spacecraft into orbit around Jupiter to perform forty-five repeated close science flybys of the icy moon, Europa. The goal is to produce high resolution images of Europa's surface and determine its composition. This will include exploration of signs of a saltwater ocean beneath the icy crust, indicating conditions habitable for life.

One of the key technical challenges for this flight system is the extreme Jovian trapped radiation environment, which is especially harsh at Europa. This severe radiation environment poses a significant risk to mission performance and lifetime [1], and requires electronic parts that must survive very stressing total dose levels.

The current spacecraft design is intended to mitigate the cumulative effects of total ionizing dose (TID) in the Jovian radiation environment (primarily from high energy trapped electrons) through a combination of radiation hardened parts selection and shielding. In particular, the accumulated total dose, over the course of the mission, will be attenuated from 2.7 MRad(Si) to 150 kRad(Si) using a protective radiation vault. The shielding vault is designed with ~500 mil aluminum walls to house most of the spacecraft and payload electronics and is similar to the configuration used on the Juno mission [1].

In addition, a radiation design factor (RDF) of two is applied to the 150 kRad(Si) internal operational environment for the vault electronics. Therefore, given the present shielding design, it is required that electronic components are capable of operating up to a TID level of 300 kRad(Si) at the part location. The RDF of two provides a systematic approach to managing the risk posed by uncertainties in the predicted external radiation environment and subsequent transport models as well as hardware susceptibility [1].

In general, electronics are exposed to ionizing radiation in the space environment at a low dose rate. As a result, parts fabricated on bipolar linear and Bipolar Complementary Metal Oxide Semiconductor (BiCMOS) process technologies can experience far greater degradation than if the same level of TID is accumulated at a high dose rate. This phenomenon is known as enhanced low dose rate sensitivity (ELDRS). As a result, the TID sensitivity of parts containing bipolar elements cannot be determined from tests at higher dose rates, even by adding additional factors for enhanced damage. Therefore, ELDRS testing on linear bipolar and BiCMOS devices is essential to the success of the Europa Clipper mission to ensure flight parts will operate within application specific requirements following exposure to this harsh ionizing radiation environment.

The purpose of this compendium is to serve as a reference to highlight recent TID test data out to 300 kRad(Si) in support of the Europa Clipper spacecraft design. The focus is on devices fabricated on bipolar and BiCMOS process technologies, which require low dose rate radiation testing to characterize the ELDRS performance. However, a few CMOS parts that were part of the recent Europa Clipper test campaign are also included in this paper as a result of their criticality to the success of the project.

Overall, the intent of this paper is to document trends and key degradation factors in the radiation sensitivity of a variety of flight critical components that are being considered for use in this very stressing radiation environment. A discussion of annealing effects and irradiation bias dependency in the

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collected data is also provided where applicable.

II. DATA ORGANIZATION

This paper summarizes recent total dose test results performed by the Jet Propulsion Laboratory, California Institute of Technology from 2016 to 2018 in support of the Europa Clipper mission. Experimental data is provided for over twenty different device types built on bipolar, BiCMOS, and CMOS process technologies across various manufacturers.

In Section III, the test facilities and experimental methods are identified, while a detailed discussion of the TID test results for six commonly used devices is provided in Section IV. Table II of Section VIII contains all of the details for the collected TID data, including the generic part number, flight procurement part number, date code, lot number, manufacturer, part description, process technology, bias, dose level for parametric/functional failure, and an overall summary of the test results. Note, the final summary table only contains abbreviated information. It is highly recommended for the reader to contact the authors of this paper for additional test report details.

III. EXPERIMENTAL PROCEDURE

A. Experimental Methods

As discussed, the expected accumulated total dose level inside the Europa Clipper electronics vault is 150 kRad(Si). Applying the RDF of two, in order to mitigate risk, it is required that electronic parts are capable of operating up to 300 kRad(Si). At this dose level, standard test methods used to characterize devices and to perform Radiation Lot Acceptance Testing (RLAT) would require one year to complete at a dose rate of 10 mRad(Si)/s (per MIL-STD-883, Test Method 1019, Condition D). This would pose a significant impact and risk to the project schedule. Thus, a Risk Reduction task was initiated to determine a shorter duration ELDRS test method to address the mission dose profile.

The study determined total dose characterization and radiation lot acceptance testing of bipolar and BiCMOS devices shall be performed in accordance with MIL-STD-883, Method 1019, Condition C, at a dose rate derived from the mission dose profile.

The mission trajectories under consideration for EC consist of multiple flybys near Europa using elliptical orbits minimize the amount of time spent in the harsh Jovian radiation belts. This approach minimizes the high radiation exposure to intermittent times of close proximity in which science data is acquired.

Most of the mission dose is received during each flyby which lasts about 48 hours. During this time, the dose rate profile inside the electronics vault varies up to a maximum of ~140 mRad(Si)/s (assuming 500 mil thick aluminum walls). For most of the remainder of the orbital period, 10-12 days, the total dose received is almost negligible.

Based on the flyby mission trajectory, coupled with the assumed vault shielding configuration and the expected 300 kRad(Si) internal operational environment (with an RDF of two applied), the appropriate dose rate for all Europa Clipper ELDRS testing on bipolar and BiCMOS devices was determined to be ~45 mRad(Si)/s ± 15%. This value was chosen because it is below the average dose rate at which 90% of the mission dose is received.

It should also be noted, as part of this Europa Clipper test campaign, bulk CMOS parts, which are not low dose rate sensitive, were tested at an intermediate dose rate of 100 mRad(Si)/s (as opposed to the standard Method 1019, Condition A dose rate of 50-300 Rad(Si)/s). This dose rate was chosen for scheduling convenience while avoiding annealing at each dose interval.

For all of the candidate parts discussed in this paper, the TID irradiation was performed at ambient room temperature (25°C). The parts were operated under both biased and unbiased test conditions during irradiation. A step-stress model was implemented which includes the following irradiation endpoints: 100 kRad(Si), 150 kRad(Si), 200 kRad(Si), 225 kRad(Si), 250 kRad(Si), 275 kRad(Si) and 300 kRad(Si). Electrical characterization was performed at room temperature prior to irradiation and after each aforementioned dose level. All limits and test conditions were derived from Table I of the applicable standard microcircuit drawing (SMD) or MIL-PRF specification for each device. Note, off-specification testing was not covered by this work. Test conditions included implementation of the worst case bias voltage, intended to bound part performance. In some cases, electrical characterization was performed by the part vendors, which is discussed in more detail in Section IV, where applicable. A minimum sample size was identified as five devices per wafer/diffusion lot per test condition. If wafer lot traceability was not available, then the sample size was increased to ten per test condition.

B. Test Facilities

All irradiations were performed using the low dose rate Cobalt-60 total ionizing dose source on site at the Jet Propulsion Laboratory in Pasadena, CA. The low dose rate source is manufactured by J.L. Sheppard and Associates and is a room irradiator. The cell is calibrated with traceability to NIST standards. The ~45 mRad(Si)/s and 100 mRad(Si)/s dose rates were controlled by adjusting the distance between the test articles and the radiation source. Dose rate measurements were performed during the first week of every month of irradiation, and distances were adjusted accordingly to maintain consistent exposure conditions. For some device types, the pre- and post-irradiation electrical characterizations were performed by the manufacturers at their production facilities. These contributions are acknowledged at the end of this paper.

IV. TEST RESULTS AND DISCUSSION

1) Semicoa JANSF2N2907A and JANSF2N2857

Two bipolar junction transistors (BJTs) have been characterized for low dose rate sensitivity for the Europa Clipper mission. The 2N2907A is a PNP device from wafer lot SQ9, lot date code 1120 while the 2N2857 is a NPN BJT from wafer lot J1939/AL03, lot date code 1124. Both device types are manufactured by Semicoa.

A total of 20 samples (10 biased and 10 unbiased) of each device type were irradiated at a low dose rate of ~45 mRad(Si)/s). As discussed previously, the irradiation was performed at JPL to an accumulated exposure of 300 kRad(Si) per MIL-STD-750, Method 1019, Condition C.

For both tests, a +12V DC bias was applied. For the unbiased testing, all leads were shorted together in a conductive foam. Five control samples served as a check on the validity of the measurement system and did not demonstrate any considerable parametric degradation as a function of total dose. The pre- and post-irradiation electrical characterization was performed by Semicoa in Costa Mesa, CA.

Based on the raw data for the 2N2907A, all 10 of the biased and unbiased parts met the MIL-PRF-19500/291W Table II, Group D, Subgroup 2 limits up to and including 300 kRad(Si). In general, the 10 unbiased parts performed slightly worse than the biased devices, indicating bias dependency in the data.

There were a few 99/90 statistical non-compliances with the Table II spec limits. Specifically, there was a N99/90H violation for the base-emitter saturation voltage [VBESAT1 (IC = -150mA, IB = -15mA)] on the biased parts starting at 200 kRad(Si). The high value falls slightly below the minimum spec limit by a delta of 46 mV. Post 300 kRad(Si), a delta of 69.4 mV (below the minimum spec limit) was calculated for VBESAT1. The other two parametric failures for the unbiased samples occurred at 275 kRad(Si) and include the collector-base cutoff current [ICBO2 (VCB = -50V)] and collector-emitter cutoff current [ICES (VCB = -50V)]. Both 99/90 parametric non-compliances were observed for serial number 454 only. The maximum spec limit was exceeded by 1.3 μA in both cases. Overall, despite some minor gain degradation, all of the parts (biased and unbiased) still met the remaining MIL-PRF limits.

For the 2N2857 devices, all 10 of the biased and unbiased parts met the MIL-PRF-19500/343M Table II, Group D, Subgroup 2 spec limits up to and including 300 kRad(Si). There were no parametric (including 99/90 non-conformances) or functional failures observed during the course of the test.

It should also be noted, the DC current gain (h_{FE}) is the most radiation sensitive parameter for both of these BJT devices. During the course of the tests, there was stable gain degradation observed across radiation for both the biased and unbiased test conditions. Post 300 kRad(Si), all measured DC current gain parameters for the two part types were well above the minimum specified MIL-PRF-19500 Table II limits. Figures 1 and 2 plot raw data for the gain measurement (h_{FE1}) as a function of low dose rate radiation (biased and unbiased) for the 2N2907A and 2N2857. The trendlines are stable out to 300 kRad(Si).

In terms of $\Delta(1/h_{FE})$, the unbiased devices showed a slightly worse response as compared to the biased test samples. There was less bias dependency noted in the 2N2857 data as compared to the 2N2907A for the current gain. These trends in $\Delta(1/h_{FE})$ are shown in Figures 3 and 4 for both part types. High dose rate testing was also performed on the same 2N2907A and 2N2857 wafer lots out to 300 kRad(Si) and showed worse gain degradation overall as compared to the low dose rate response.

Overall, the parameters discussed in detail herein (specifically the base-emitter saturation voltage and current gain) for these devices are critical to any design, either in a switch or amplifier application.

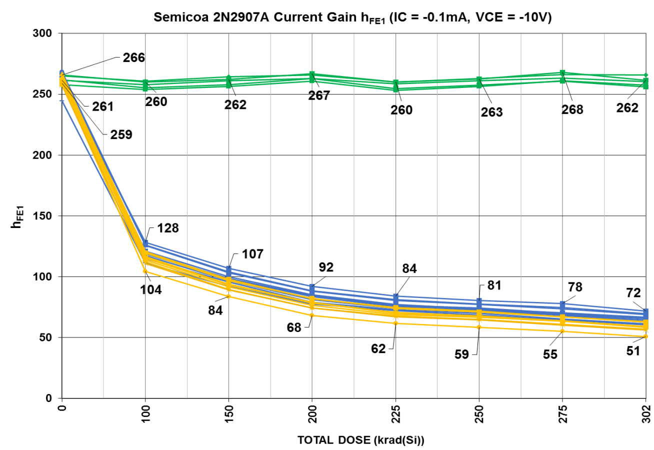

Fig. 1. DC current gain (raw data) for Semicoa 2N2907A as a function of low dose rate irradiation out to 300 kRad(Si). Biased devices are shown by the blue trendlines, while orange is used to represent the unbiased measurements. The control readings are plotted in green.

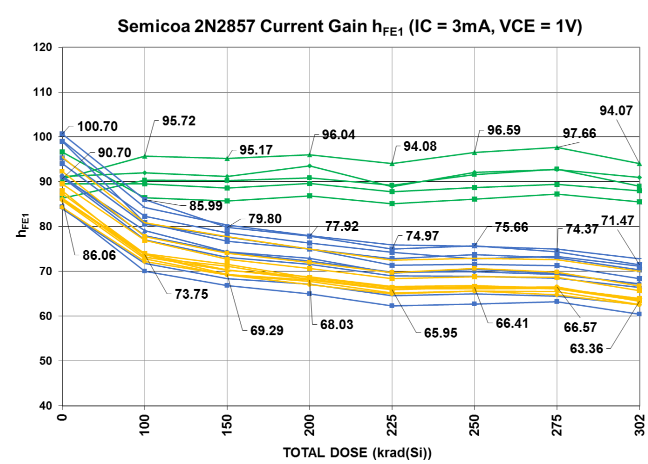

Fig. 2. DC current gain (raw data) for Semicoa 2N2857 as a function of low dose rate irradiation out to 300 kRad(Si). Biased devices are shown by the blue trendlines, while orange is used to represent the unbiased measurements. The control readings are plotted in green.

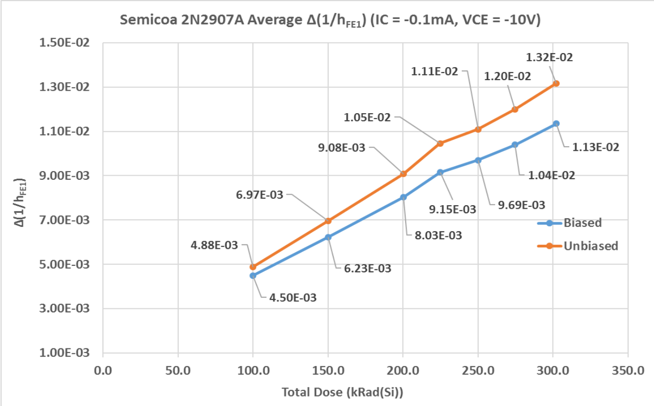

Fig. 3.Semicoa 2N2907A average Δ(1/h_{FE}) for (Ic=-0.1mA) as a function of low dose rate irradiation out to 300 kRad(Si).

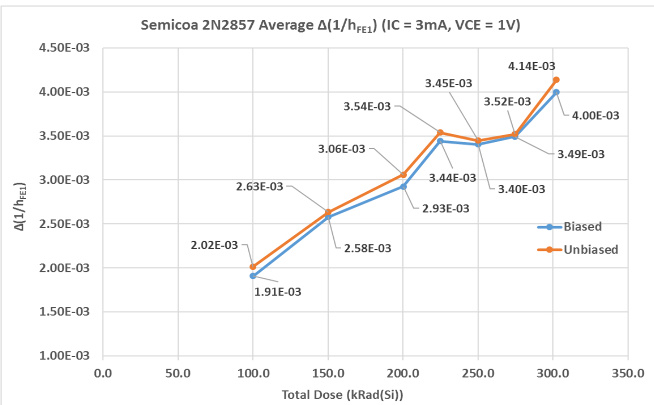

Fig. 4. Semicoa 2N2857 average Δ(1/h_{FE}) for (Ic=3mA) as a function of low dose rate irradiation out to 300 kRad(Si).

2) Renesas ISL70003ASEH (5962R1420302VYC)

The Renesas (formerly Intersil) ISL70003SEH is a radiation hardened 12V point-of-load (POL) regulator designed on a BiCMOS process optimized for power management. Critical parameters for this device include the reference voltage, oscillator frequency, drain-source on-state resistance and undervoltage lockout.

This part was previously characterized by Renesas up to 150 kRad(Si) at low dose rate (10 mRad(Si)/s) with minimal parametric degradation [2]. Per the SMD, the part is guaranteed to 100 kRad(Si) at HDR and 50 kRad(Si) at LDR.

As part of the Europa Clipper test campaign, 10 samples were Co-60 gamma irradiated (5 biased and 5 unbiased during irradiation) at the mission low dose rate of 42 mRad(Si)/s to an accumulated exposure of 300 kRad(Si). Two additional samples were used as controls and were not irradiated. The irradiation was performed at ambient room temperature by JPL. The pre- and post-irradiation electrical characterization was performed by Renesas at their manufacturing center in Palm Bay, FL. All test devices originated from wafer lot 4Q01BGBA.

The devices were biased during irradiation at 13.20V and the parametric tests were performed at PVin = 5.5V and 3V (where applicable). The unbiased and biased radiation samples were mounted on their own individual bias cards during irradiation. For the unbiased testing, all leads were shorted together using the ground plane of the bias card.

Based on the raw data, there were no parametric or functional failures observed during the course of the test. All five of the biased and five unbiased parts parametrically met the 5962-14203 Table I spec limits up to and including 300 kRad(Si).

A plot of drain-source on-state resistance, Rds(on), at 5.5V and 3V is provided in Figures 5 and 6 to demonstrate the stability of this part out to 300 kRad(Si). This is a critical parameter for the efficiency of this device. Figure 7 plots the reference voltage (at 4V) and Figure 8 shows the leakage current response for the logic pins that enable/disable the inputs of the device (for V_{IH} voltage). Overall, there was no bias dependency indicated by the test results and all plots looked very stable across radiation.

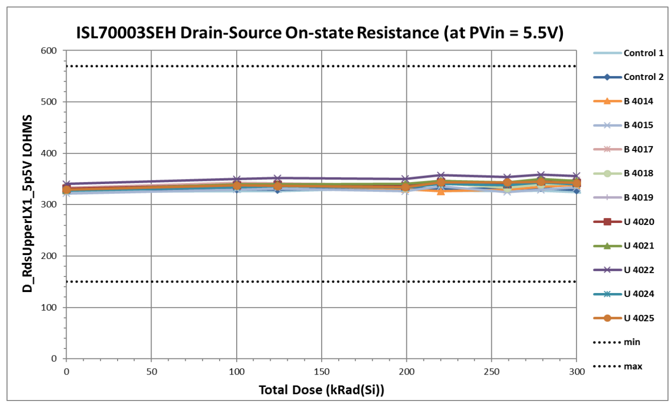

Fig. 5. ISL70003SEH drain-source on-state resistance (at PVin = 5.5V) as a function of LDR TID for parts biased and unbiased during irradiation. All test samples showed a very stable response and remained within specification out to 300 kRad(Si).

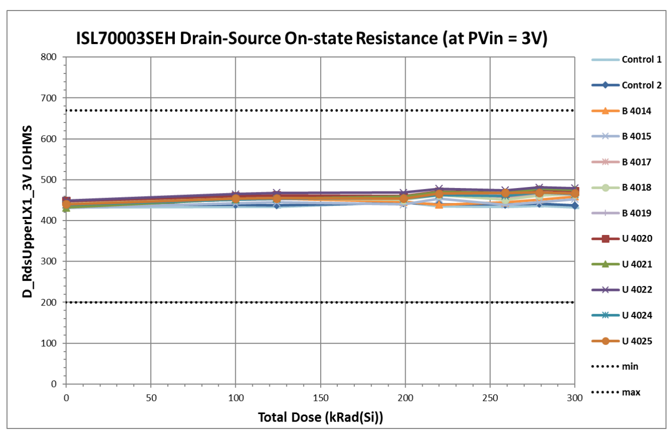

Fig. 6. ISL70003SEH drain-source on-state resistance (at PVin = 3V) as a function of LDR TID for parts biased and unbiased during irradiation. All test samples showed a very stable response and remained within specification out to 300 kRad(Si).

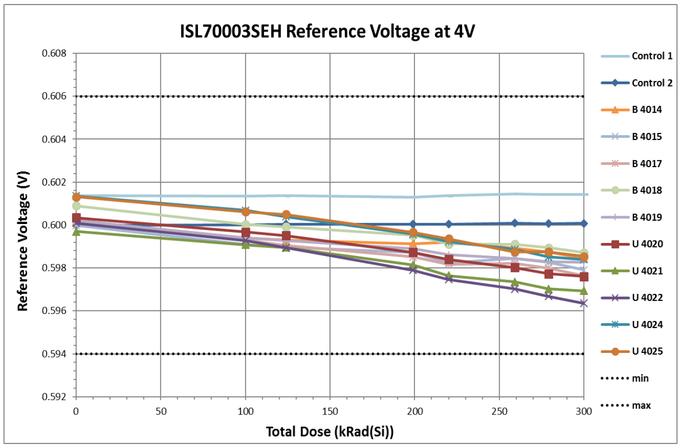

Fig. 7. ISL70003SEH reference voltage (at 4V) as a function of LDR TID for parts biased and unbiased during irradiation. All test samples showed a very stable response and remained within specification out to 300 kRad(Si).

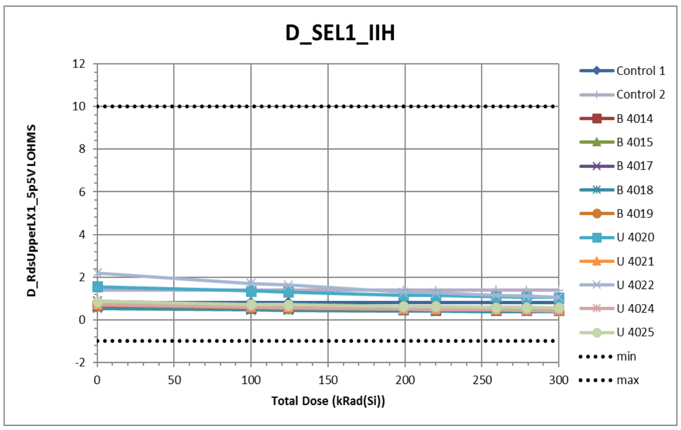

Fig. 8. ISL70003SEH leakage current response for the logic pins that enable/disable the inputs of the device (for VIH voltage) as a function of LDR TID for parts biased and unbiased during irradiation. All test samples showed a very stable response and remained within specification out to 300 kRad(Si).

3) Renesas HS-117EH (5962F9954702VXC)

The Renesas (formerly Intersil) HS-117EH is a radiation hardened adjustable positive voltage linear regulator capable of operating with input voltages up to 40V.

This part was previously characterized by Renesas up to 50 kRad(Si) at low dose rate (10 mRad(Si)/s) with minimal parametric degradation [3]. Per the SMD, the part is guaranteed to 300 kRad(Si) at HDR and 50 kRad(Si) at LDR.

Ten samples were Co-60 gamma irradiated (5 biased and 5 unbiased during irradiation) at the mission low dose rate of 42 mRad(Si)/s to an accumulated exposure of 300 kRad(Si). Two additional samples were used as controls and were not irradiated. The electrical characterization was performed by Renesas at their manufacturing center in Palm Bay, FL. The irradiation was performed at ambient room temperature by JPL. All test devices originated from wafer lot G3W7CEAA, date code 1632.

The parts were biased during irradiation at 15V and the parametric tests were performed at V_{DIFF} = 40V and 3V per the test conditions in 5962-99547 Table I. The unbiased and biased radiation samples were mounted on their own individual bias cards during irradiation. For the unbiased testing, all leads were shorted together using the ground plane of the bias card.

Based on the raw data, only one device experienced parametric and functional failure during the course of the test (as indicated by a large drop in the output voltage). This failure was attributed to a handling issue with unbiased serial number 6651 starting at 279 kRad(Si). High dose rate on the same set of 10 test samples confirmed the functional failure of serial number 6651 was attributed to mishandling and was not radiation induced. A subsequent failure analysis showed a blown bond wire on this device.

Aside from this anomaly, all 5 biased and all 4 unbiased parts parametrically met the 5962-99547 Table I spec limits up to and including 300 kRad(Si). As expected for a linear bipolar device, the unbiased parts performed worse than the biased test samples. A plot of the reference voltage at 3V is provided in Figure 9 to demonstrate the stability of this part out to 300 kRad(Si). Note, the readings at 40V for Vref were nearly identical and the anomalous test sample has been omitted from these plots.

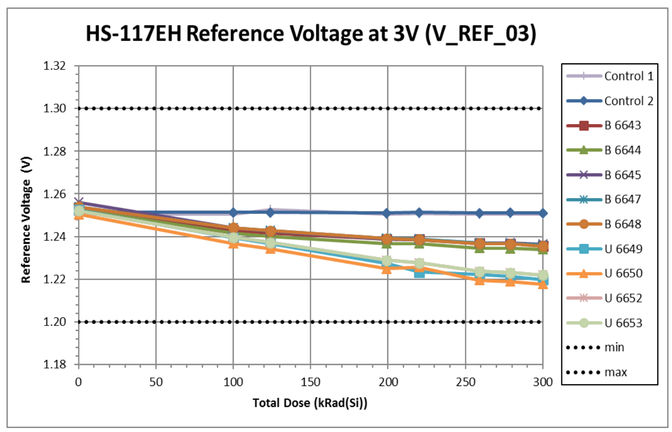

Fig. 9. HS-117EH reference voltage as a function of LDR TID for parts biased and unbiased during irradiation. All test samples remained within specification out to 300 kRad(Si) with the exception of one device that was mishandled (not depicted here).

4) Renesas HS-303AEH (5962F9581306VXC)

The Renesas (formerly Intersil) HS-303ASEH is an analog switch fabricated on the dielectrically isolated Radiation Hardened Silicon Gate (RSG) BiCMOS process technology.

Previous low dose rate testing by Intersil on the HS-303BEH at 10 mRad(Si)/s showed the device will meet the datasheet limits up to and including 150 kRad(Si). Per the SMD, the AEH version of this part is guaranteed to 300 kRad(Si) at HDR and 50 kRad(Si) at LDR.

Ten samples were Co-60 gamma irradiated (5 biased and 5 unbiased during irradiation) at the mission low dose rate of 42 mRad(Si)/s to an accumulated exposure of 300 kRad(Si). Two additional samples were used as controls and were not irradiated. The electrical characterization was performed by Renesas at their manufacturing center in Palm Bay, FL. The irradiation was performed at ambient room temperature by

JPL. All test devices originated from wafer lot DWP3TDA, date code 1645.

The parts were biased during irradiation at 15V. The unbiased and biased radiation samples were mounted on their own individual bias cards during irradiation. For the unbiased testing, all leads were shorted together using the ground plane of the bias card.

Based on the raw data, all test samples met the SMD 5962-95813 Table I electrical limits up to and including 125 kRad(Si). Parametric failures were first observed at 200 kRad(Si) for the switch turn off and turn on times, Toff and Ton. Functional failures of the unbiased test samples were first observed between 200 and 250 kRrad(Si) as indicated by the switching times. As expected for a linear bipolar device, the unbiased parts performed worse than the biased test samples. A plot of the switch turn off and turn on times are provided in Figures 10 and 11 to demonstrate the radiation induced degradation of this part out to 300 kRad(Si).

Following the low dose rate TID test, a 50°C anneal was performed for 48 hours. The functionally failed devices did not recover as a result of the anneal.

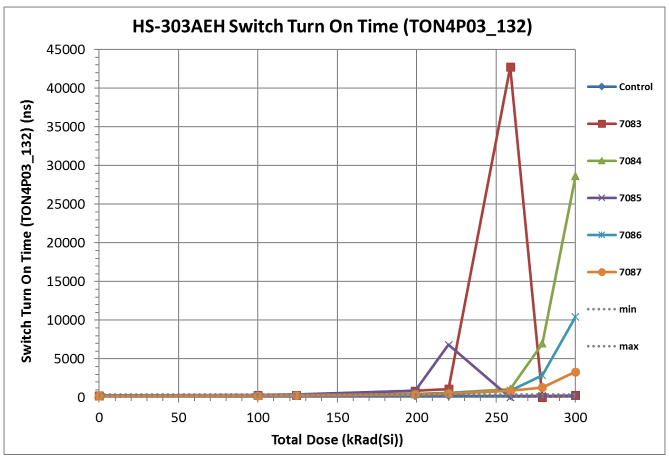

Fig. 10. HS-303AEH worst case switch turn on time as a function of LDR TID for parts unbiased during irradiation. Functional/severe parametric failures were first observed at 200 kRad(Si).

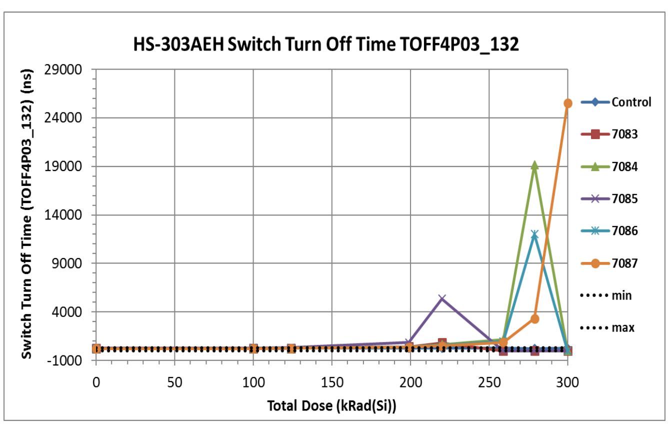

Fig. 11. HS-303AEH worst case switch turn off time as a function of LDR TID for parts unbiased during irradiation. Functional/severe parametric failures were first observed at 200 kRad(Si).

5) ST Micro RHR61 (5962R1620401VXC)

The ST Micro RHR61 is a pure bulk CMOS single rail-to-rail operational amplifier. This device is rated to 100 kRad(Si) at HDR per the ST Micro datasheet [3]. Separate TID characterization tests were performed by JPL in 2016 and 2018.

In 2016, ten samples (plus two controls) of the RHR61 (wafer lot 31533) were irradiated to an accumulated dose of 300 kRad(Si) at an exposure rate of 100 mRad(Si)/s. Five devices were biased in a generic op-amp configuration (common case) per the manufacturer recommended bias circuit. The other five devices were left unbiased during irradiation. For the parametric testing, Vin was set at 1.8V, 3.3V and 5V. Parametric failure of the supply current (Icc) was first observed starting at 50 kRad(Si). Input offset voltage was also a notable sensitive parameter which began falling out of spec at 250 kRad(Si) for Vin = 1.8V only. All other parameters met the SMD 5962-16204 Table I limits up to 300 kRad(Si). No functional failures were observed during the course of the test. Finally, the biased parts performed much worse than the unbiased devices.

In 2018, a different set of RHR61 samples were TID tested in a comparator bias configuration. The bias circuit applied a 2.5V input voltage differential using 5V supply (comparator output low 0V). Three devices were biased during irradiation and three devices were grounded. The test was performed at a HDR of ~38 Rad(Si)/s.

Significant parametric and functional failures were observed for the biased samples, and the test was stopped at 200 kRad(Si). The out of spec and/or functionally failing parameters include input offset current, bias current, supply current, offset voltage, slew rate and open loop gain. An unbiased 168 hour room temperature anneal was performed after the test completion. No recovery of functionality in any of the three failed test devices was observed (which were biased during irradiation). The unbiased parts, however, met the manufacturer datasheet limits up to and including 200 kRad(Si).

As a result of this study, a follow-on pathfinder test was performed on a new set of RHR61 samples. The purpose of this additional test was to have better visibility as to when the output gets stuck low, and how the input offset voltage changes with radiation. For three test samples the input differential voltage was varied on the bias to include measurements for 0V, 0.5V, 1.0V, and 2.0V. The test was run at room temperature with a high dose rate of ~40 Rad(Si)/s. When biased as a voltage follower, functional failures were observed starting at 150 kRad(Si). Under bias with varying input voltage differential, functional failures were observed beginning at 62 kRad(Si). It was noted, as the input differential voltage is increased, the results get worse until saturation is reached. An unbiased 168 hour room temperature anneal was performed after the test completion. No recovery of functionality in any of the failed test devices was observed.

From a design perspective, it is not recommended to use standard op-amps in a comparator configuration in a stressing total dose radiation environment such as that of Europa

Clipper's. As the differential voltage across the inputs is increased, the device's internal bias current can drastically increase, in proportion to the input differential, beyond the capability of the part, resulting in damage to the IC.

As part of a future test effort, scheduled for Fall 2018, JPL is planning on re-characterizing the ST Micro RHR61 and RHR64 at a moderate total dose rate of 100 mRad(Si)/s which is more representative of the Europa Clipper mission dose profile (as opposed to a high dose rate). Twenty devices from different flight wafer lots will be biased in both a generic op-amp and comparator configuration for completeness. The total dose irradiation will be taken out to an accumulated dose of 300 kRad(Si).

6) Analog Devices RH1013 (5962R8876003VHA)

The Analog Devices RH1013 is a dual precision operational amplifier previously characterized by Analog Devices to 100 kRad(Si) at low dose rate (10 mRad(Si)/s) [4]. Per this test report, all parts remained within the datasheet limits out to 100 kRad(Si).

For the Europa Clipper test campaign, a total of 10 samples were Co-60 gamma irradiated (5 biased and 5 unbiased during irradiation) at low dose rate of 42 mRad(Si)/s to an accumulated exposure of 300 kRad(Si). An additional eleventh sample was used as a control, which was not irradiated. Both the irradiation and pre- and post- electrical characterization were done at room temperature using JPL facilities. Parametric characterization was performed to the specifications and test conditions provided in 5962-88760, Rev G, Table I. The part was biased during irradiation at ±15V and the parametric tests were performed at a supply voltage of ±15V and 5V. All eleven test samples originated from wafer lot A21617.1 (IR1220375) and date code: 1650A.

After accumulated exposure up to 300 kRad(Si), this device continued to meet all SMD specification limits with minimal parametric degradation and no functional failures observed. As expected, in most cases, the unbiased parts performed worse than the biased devices, indicating bias dependency in the data. The most sensitive parameter appeared to be the offset voltage (as plotted in Figure 12) with the largest recorded delta shifts out to 300 kRad(Si). Although, as previously mentioned, all measured parameters were very stable throughout the duration of the test. Table I provides a summary of the mean worst case parametric deltas out to an accumulated exposure of 300 kRad(Si).

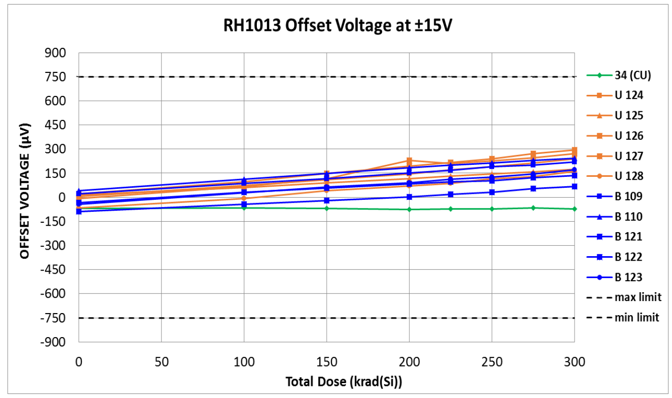

Fig. 12. RH1013 offset voltage as a function of LDR TID out to 300 kRad(Si) for parts unbiased and biased during irradiation. Parametric test was performed at ±15V. All test samples showed a very stable response and remained within spec out to 300 kRad(Si).

TABLE I

SUMMARY OF RH1013 MEAN WORST CASE RADIATION-INDUCED DELTAS (BASED ON RAW DATA) FOR CRITICAL PARAMETERS

TEST PARAMETER	TID EXPOSURE LEVEL (kRad(Si)							UNITS
	100.0	150.0	200.0	225.0	250.0	275.0	300.0	
ICC (VS = ± 15V) B	0.13	0.19	0.24	0.25	0.27	0.28	0.30	mA
ICC (VS = ± 15V) UNB	0.08	0.13	0.19	0.21	0.24	0.27	0.29	mA
IEE (VS = ± 15V) B	0.12	0.18	0.24	0.25	0.27	0.29	0.30	mA
IEE (VS = ± 15V) UNB	0.08	0.13	0.19	0.22	0.24	0.27	0.30	mA
ICC @ +5V B	0.11	0.15	0.18	0.19	0.20	0.21	0.22	mA
ICC @ +5V UNB	0.08	0.13	0.17	0.19	0.20	0.22	0.23	mA
IEE @ +5V B	0.11	0.15	0.18	0.19	0.20	0.21	0.22	mA
IEE @ +5V UNB	0.08	0.13	0.17	0.19	0.20	0.22	0.23	mA
OFFSET VOLTAGE @ ±15V B	62.06	91.82	114.43	128.33	142.07	156.58	175.33	µV
OFFSET VOLTAGE @ ±15V UNB	85.74	132.12	180.13	204.57	225.10	252.74	279.03	µV
OFFSET VOLTAGE @ +5V B	65.97	92.81	110.62	119.06	128.67	138.47	152.95	µV
OFFSET VOLTAGE @ +5V UNB	99.22	145.66	197.10	220.22	243.11	268.12	298.27	µV
I OFFSET @ ±15V B	0.39	0.48	0.59	0.50	0.55	0.59	0.42	nA
I OFFSET @ ±15V UNB	0.94	1.09	2.37	2.36	2.71	3.07	3.28	nA
I OFFSET @ +5V B	0.20	0.26	0.27	0.12	0.13	0.13	0.01	nA
I OFFSET @ +5V UNB	1.14	1.52	2.64	2.52	2.72	2.91	3.03	nA
Ibias (VS = ± 15V) B	32.45	46.67	58.01	64.57	69.79	75.15	79.83	nA
Ibias (VS = ± 15V) UNB	21.45	30.07	38.54	42.83	47.01	50.90	55.13	nA
Ibias (VS = +5V) B	35.22	49.99	61.10	67.54	72.38	77.18	81.34	nA
Ibias (VS = +5V) UNB	24.47	34.24	42.40	46.52	50.09	52.95	55.87	nA
CMRR +13V > -15V B	4.89	5.04	5.37	5.08	5.07	5.02	5.23	dB
CMRR +13V > -15V UNB	5.67	6.46	7.16	7.47	7.96	8.39	8.75	dB
PSRR ±10V TO 18V B	7.21	8.29	8.14	7.31	5.83	2.98	1.27	dB
PSRR ±10V TO 18V UNB	1.33	1.39	13.37	14.50	16.84	16.71	19.47	dB
AVOL RL=10K VO=0>+10V B	127.03	128.67	123.52	118.29	120.72	119.74	122.20	dB
AVOL RL=10K VO=0>+10V UNB	124.09	131.05	130.23	126.51	128.78	129.79	130.74	dB
VOUT RL=10K @ ±15V B	0.01	0.02	0.02	0.03	0.03	0.04	0.05	V
VOUT RL=10K @ ±15V UNB	0.00	0.01	0.01	0.02	0.02	0.03	0.03	V
VOUT RL=OPEN @ +5V B	0.06	0.06	0.06	0.06	0.06	0.06	0.06	V
VOUT RL=OPEN @ +5V UNB	0.03	0.06	0.06	0.06	0.06	0.06	0.06	V
VOUT RL=600 @ +5V B	0.01	0.01	0.01	0.01	0.01	0.02	0.02	V
VOUT RL=600 @ +5V UNB	0.01	0.01	0.02	0.02	0.02	0.02	0.02	V
VOUT IL=1MA @ +5V B	0.02	0.04	0.37	0.41	0.84	0.92	0.96	V
VOUT IL=1MA @ +5V UNB	0.01	0.02	0.04	0.05	0.30	0.87	0.94	V
ISOURCE @ ±15V VO=10V B	0.37	0.48	0.25	0.61	0.60	0.60	0.66	mA
ISOURCE @ ±15V VO=10V UNB	0.30	0.45	0.27	0.54	0.58	0.53	0.57	mA
ISINK @ ±15V VO=-10V B	0.64	0.86	0.67	1.12	1.14	1.18	1.30	mA
ISINK @ ±15V VO=-10V UNB	0.52	0.76	0.64	0.97	1.07	1.05	1.15	mA
SLEW RATE AV=1 @ ±15V B	0.07	0.10	0.13	0.13	0.14	0.15	0.13	V/µs
SLEW RATE AV=1 @ ±15V UNB	0.05	0.08	0.11	0.11	0.12	0.13	0.16	V/µs

V. CONCLUSION

The purpose of this compendium is to serve as a reference to highlight recent TID test data out to 300 kRad(Si) in support of NASA JPL's Europa Clipper mission. The focus is on devices fabricated on bipolar and BiCMOS process technologies, which require low dose rate radiation testing to characterize the ELDRS performance. One CMOS part is also discussed due to its interesting TID response as well as its criticality to the success of the project.

Overall, this paper documents trends and key degradation factors in the radiation sensitivity of a variety of flight critical components that are being considered for use in this very stressing Jovian radiation environment. A discussion of annealing effects and irradiation bias dependency in the collected data has also been provided.

In summary, a majority of the devices were fully functional out to 300 kRad(Si) with minor parametric degradation. In a few instances, where noted, some part types will require local shielding in order to meet the project requirements. However, it is important to note, many of these devices have been stressed beyond their existing manufacturer datasheet ratings in order to document compliance with this challenging Europa Clipper 300 kRad(Si) total dose radiation requirement.

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VII. REFERENCES

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VIII. SUMMARY OF TEST RESULTS

TABLE II
SUMMARY OF EUROPA CLIPPER LOW DOSE RATE TOTAL IONIZING DOSE (TID) TEST RESULTS

Part Number	Flight Procurement Number	Part Description	Mfr.	Process Tech.	Test Facility (Test Date)	Wafer Lot / Date Code	Test Sample Size	Supply Voltage (V)	Parametric Deg. Level (kRad(Si))	Func. Failure (kRad(Si))	Summary of Test Results
2N2907A	JANSF2N2907A	PNP Bipolar Junction Transistor	Semicoa	Bipolar	JPL / Semicoa (April 2017)	SQ9; LDC: 1120	10 (biased) 10 (unbiased)	12	200	>300	All parts (biased and unbiased) parametrically meet spec limits (including current gain) out to 300 kRad(Si). No functional failures. Unbiased parts performed slightly worse than biased. Starting at 200 kRad(Si), 99/90 high value for VBESAT1 on biased parts exceeds spec. At 300 kRad(Si), VBESAT1 is 69.4 mV below min spec limit. At 275 kRad(Si), ICBO2 and ICES exceed max spec limit by delta of 1.3 µA (in both cases).
2N2857	JANSF2N2857	NPN Bipolar Junction Transistor	Semicoa	Bipolar	JPL / Semicoa (April 2017)	J1939/AL03 ; LDC: 1124	10 (biased) 10 (unbiased)	12	>300	>300	All parts (biased and unbiased) meet spec limits (including current gain) parametrically out to 300 kRad(Si). No functional failures post 300 kRad(Si).
IS-139ASEH	5962F0151002VXC	Quad Voltage Comparator	Renesas / Intersil	Bipolar / dielectrically isolated (DI) RSG	JPL / Intersil (Dec 2017)	G3P3WEH; LDC: 1622	5 (biased) 5 (unbiased)	15	200	>300	Parametric failure of bias current and open loop gain starting at 200 krad(Si). At 260k, 280k and 300 kRad(Si) open loop gain saturated at 12 dB. There were no AC parametric fails and no functional fails out to 300 kRad(Si). However, the drop in gain is quite measurable at 260 kRad(Si).
HS-508BEH	5962F9674203VXC	8-Channel Analog Multiplexer	Renesas / Intersil	BiCMOS	JPL / Intersil (Dec 2017)	DWL3VBA; LDC: 1627	5 (biased) 5 (unbiased)	±15	>300	>300	Parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures post 300 kRad(Si).
ISL71590 SEH	5962F1321501VXC	2 Terminal Temperature Transducer	Renesas / Intersil	Bipolar / dielectrically isolated (DI) RSG	JPL / Intersil (Dec 2017)	X0V5HAU; LDC: 1701	5 (biased) 5 (unbiased)	5.2	100	>300	Unbiased samples parametrically failed temperature error (TERR) limit starting at 100 kRad(Si). Worse TERR reading was -5.7 µa at 300 kRad(Si). No functional failures post 300 kRad(Si).
HS-117EH	5962F9954702VXC	Positive Voltage Regulator, 40V, 50W	Renesas / Intersil	Bipolar	JPL / Intersil (Dec 2017)	G3W7CEA A and G3W7CD; LDC: 1632	5 (biased) 5 (unbiased)	15	>300	>300	One unbiased unit failed functionally starting at 279 kRad(Si). Failure was attributed to handling error. Aside from this anomaly, all 5 biased and all 4 unbiased parts parametrically met respective SMD limits out to 300 kRad(Si). Unbiased parts performed worse than biased. No functional failures post 300 kRad(Si) (on 9 parts).

Part Number	Flight Procurement Number	Part Description	Mfr.	Process Tech.	Test Facility (Test Date)	Wafer Lot / Date Code	Test Sample Size	Supply Voltage (V)	Parametric Deg. Level (kRad(Si))	Func. Failure (kRad(Si))	Summary of Test Results
HS-303AEH	5962F9581306VXC	Radiation Hardened DI, Dual SPDT Switch	Renesas / Intersil	BiCMOS	JPL / Intersil (Dec 2017)	DWP3TDA; LDC: 1645	5 (biased) 5 (unbiased)	±15	200	220	Parametric failures of Ton/Toff starting at 200 kRad(Si). Functional failures of unbiased parts first observed in 220-250 kRad(Si) range as indicated by switch turn off/on times. At 300 kRad(SI) all biased and unbiased parts fail DC and AC functionals. Following TID test, 50°C anneal performed for 48 hours; functionally failed devices did not recover.
ISL74422 BRH	5962F0324801VXC	Non-inverting MOSFET Driver, digital-linear	Renesas / Intersil	Bipolar	JPL / Intersil (Dec 2017)	DCFN8ACA A; LDC: 1449	5 (biased) 5 (unbiased)	15	>300	>300	Parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures observed post 300 kRad(Si).
ISL70003 ASEH	5962R1420302VYC	Rad tolerant 3V to 13.2V, 9A Buck Regulator	Renesas / Intersil	Bipolar	JPL / Intersil (Dec 2017)	4Q01BGBA	5 (biased) 5 (unbiased)	13.2	>300	>300	Critical parameters include reference voltage, oscillator frequency, drain-source on-state resistance and undervoltage lockout. All devices parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures observed post 300 kRad(Si).
HS-OP470AE H	5962R9853302VXC	Rad Hard Monolithic, Low-Noise Quad Op-amp	Renesas / Intersil	Bipolar	JPL (Feb 2018)	G2A7TBCA ; LDC: 1514	5 (biased) 5 (unbiased)	±15	100	>300	Unbiased test condition is worse case. Starting at 100 kRad(Si), bias current, input offset current and open loop gain begin to fall out of spec. This is the most sensitive parameter. No functional failures observed post 300 kRad(Si).
HS-1840BEH	5962F9563005VYX	Digital-Linear, Single 16-Channel Analog Mux/Demux	Renesas / Intersil	Bipolar	JPL (Feb 2018)	G0A3MF; LDC: 1740	5 (biased) 5 (unbiased)	±15	>300	>300	Parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures observed post 300 kRad(Si).
HS-201SEH	5962F9961802VXC	Rad Hard, Monolithic Analog Switch	Renesas / Intersil	BiCMOS	JPL (Feb 2018)	E0P8WDB B; LDC: 1712	5 (biased) 5 (unbiased)	±15	>300	>300	Parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures observed post 300 kRad(Si).
HS-4423RH	5962F9951101VXC	Rad Hard Inverting, Dual, High-Speed MOSFET Driver	Renesas / Intersil	Bipolar	JPL (Feb 2018)	DAXD6F; LDC: 0946	5 (biased) 5 (unbiased)	15	>300	>300	Parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures observed post 300 kRad(Si).
IS-1825SEH	5962F0251105VXC	Pulse Width Modulator, Dual Output with SEU Protection	Renesas / Intersil	Bipolar	JPL (Feb 2018)	G3H5TEH; LDC: 1603 and 1622	5 (biased) 5 (unbiased)	15	100	>300	Bias dependency not observed in data. Very minor parametric failures: error amp bias current, PWM threshold, current limit stop voltage threshold, over current limit stop voltage threshold. No functional failures observed post 300 kRad(Si).

Part Number	Flight Procurement Number	Part Description	Mfr.	Process Tech.	Test Facility (Test Date)	Wafer Lot / Date Code	Test Sample Size	Supply Voltage (V)	Parametric Deg. Level (kRad(Si))	Func. Failure (kRad(Si))	Summary of Test Results
RH1013MW	5962R8876003VHA	Dual Precision Op-amp	Analog Devices	Bipolar	JPL (Nov 2017)	A21617.1, IR122037, W1642984.1; LDC: 1650	5 (biased) 5 (unbiased)	±15	>300	>300	Parametrically passed 300 kRad(Si) LDR endpoint for both biased and ground conditions per the respective SMD. No functional failures post 300 kRad(Si).
RHR61	5962R1620401VXC	Rad Hard Microcircuit, Low Power Rail-to-Rail Single Op-amp	ST Micro	CMOS	JPL (Oct 2016)	31533	5 (biased) 5 (unbiased)	5	250	>300	Low dose rate test performed at 100 mRad(Si)/s. Biased parts performed worse than unbiased. Parametric failure of supply current starting at 50 kRad(Si). Input offset voltage, also a notable sensitive parameter, fell out of spec at 250 kRad(Si) for Vin = 1.8V only. All other parameters met SMD 5962-16204 Table I limits post 300 kRad(Si). No functional failures post 300 kRad(Si).
RHR61	5962R1620401VXC	Rad Hard Microcircuit, Low Power Rail-to-Rail Single Op-amp	ST Micro	CMOS	JPL (May 2018)	33523001ZW/1 and 33523001ZY/4; LDC: 1534	20 (comparator bias) 20 (biased as op-amp)	5	TBD	TBD	Low dose rate test (100 mRad(Si)/s) expected to complete September 2018. 20 parts to be biased as comparator and 20 parts to be biased in generic op-amp configuration. Pathfinder HDR test at ~40 Rad(Si)/s showed functional failures in both op-amp (at 150k) and comparator (at 62k) configurations. When biased as a comparator, results get worse as input differential voltage increases until saturation is reached. Most sensitive parameters include: input offset current, bias current, supply current, offset voltage, slew rate and open loop gain. Failed test devices did not recover functionality after unbiased 168 hour room temp anneal.
ISL75052SEH	5962R1322001VXC	1.5A, Rad Hard Positive, High Voltage LDO	Renesas / Intersil	Bipolar	JPL (June 2018)	3S56BDAA and 3S56BEA, LDC: 1648 and 1650	5 (biased) 5 (unbiased)	13.3	TBD	TBD	Low dose rate test expected to complete August 2018. Preliminary high dose rate testing (~50 Rad(Si)/s) completed. All biased and unbiased parts still functioning post 300k. Minor Vout failures post 300k at 2.5V. A 124 hour room temp anneal was performed under bias and all parts passed electrical tests post 300 kRad(Si).
ISL729991RH	5962F0250301VXC	Voltage Regulator, Negative, Low Dropout	Renesas / Intersil	Bipolar	JPL (July 2018)	DD4T4GBB and DHX8PG; LDC: 1533 and 1605	5 (biased) 5 (unbiased)	-25	TBD	TBD	Low dose rate test expected to complete August 2018.
ISL73128EH	5962F0721806VXC	Transistor Array, All PNP, Ultra High Frequency	Renesas / Intersil	Bipolar	JPL (July 2018)	DPP2XRAEH/B; LDC: 1435	5 (biased) 5 (unbiased)	-5.5 -10.5	TBD	TBD	Low dose rate test expected to complete August 2018.